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CURRENT TRENDS IN DECOMPRESSION DEVELOPMENT: STATISTICS AND DATA ANALYSIS

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ABSTRACT

Since the development of the first decompression tables in 1906 by J.S. Haldane, considerable research and effort have been expended in the development of safer and more rapid decompression procedures and tables. The deterministic approach is governed by a fixed set of rules that defines the boundary between safe and unsafe dives and includes a model for gas exchange and an ascent criterion, such as gas supersaturation, to calculate the "safe" decompression depth. These decompression models are essentially empirical and not physiological models and provide "safe" decompression only over a limited range of depth and bottom times. The statistical approach considers DCI to be a probabilistic event and uses a risk function consisting of a gas exchange component and an ascent criterion to estimate or predict the risk of DCI. The ascent criterion can be based on supersaturation or bubble growth. To determine the risk function, a large data set of precise dive data, including time, depth, gas composition, and DCI outcome, must be available to match the predicted risk with the observed data. Probabilistic models of decompression can be used to analyze dive tables and procedures, compare different tables, and develop decompression tables with a given risk level. The probabilistic approach for decompression is a very powerful technique that should lead to a better insight into the physics and physiology of decompression because of its objectivity and potential for implementing gas kinetics and bubble physics in the design of the risk functions for DCI. This should in turn lead to better table design, analysis and dive testing.

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EXECUTIVE SUMMARY

DCIEM has been involved in decompression research for over 30 years, and has successfully developed and validated a number of decompression tables for use by the Canadian Forces. These include decompression for air diving, surface-supported helium-oxygen diving, and self-contained semi-closed circuit rebreather diving for mine countermeasures. This article is a review of the traditional deterministic approach to decompression modelling and the newer probabilistic approach. The new approach to decompression modelling has the potential for developing safer and more efficient diving procedures and tables for CF diving applications.

Since the development of the first decompression tables in 1906 by J.S. Haldane, considerable research and effort have been expended in the development of safer and more rapid decompression procedures and tables. Most models of decompression that have been used to generate decompression tables have taken a deterministic approach where the boundary between "safe" and "unsafe" dives is governed by a fixed set of rules, depending on the gas exchange model and "safe ascent" criterion that are selected. These models are essentially empirical and not physiological models, providing "safe" decompression only over a limited range of depth and bottom times. Because decompression illness (DCI) is considered a binary event, it becomes logistically and financially impossible to conduct enough dives to show that a given dive profile is safe within statistical significance.

DCI should actually be considered as a probabilistic event. Decompression profiles are not just a case of being "safe" or "unsafe" but should be considered as a time-depth dosage that is related to the risk of DCI. This concept leads to the statistical approach for developing probabilistic models of decompression to estimate or predict the risk of DCI. A risk function is defined that consists of a gas exchange component and an ascent criterion. To determine the risk function, a large data set of precise dive data, including time, depth, gas composition, and DCI outcome, must be available. The parameters of the risk model are calculated iteratively by comparing the predictions of DCI from the model with the observed data until the best fit is attained by the method of maximum likelihood. The problem of having to do a a very large number of tests on a single profile as in the deterministic approach can be overcome with the statistical method since data from widely varying dive profiles, with each individual profile constituting only a small number of human tests, can be combined and used to improve parameter estimates of the probabilistic model. Probabilistic models of decompression can be used to analyze dive tables and procedures, compare different tables, and develop decompression tables with a given risk level. The probabilistic approach for decompression is a very powerful technique that opens up the potential for an entirely new concept in table design, analysis, and dive testing. Being able to investigate different risk criteria and gas kinetics should lead to a better insight into the physics and physiology of decompression.

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INTRODUCTION

Since the development of the first decompression tables in 1906 by J.S. Haldane, considerable research and effort have been expended in the development of safer and more rapid decompression procedures and tables. Haldane was the first to define a decompression schedule in terms of depth and time exposures (Hempleman, 1993). The approach taken by Haldane can be considered to be deterministic and most models of decompression that have been developed since then have taken a similar approach. Tables that have been developed to date are valid only over a limited range of depth and bottom times and it appears improbable to achieve the universal decompression model. We also do not have a complete understanding of the decompression process and of decompression illness (DCI). There are many factors that can directly and indirectly influence decompression safety, and in many cases, their exact contributions are not known. More recently, a different and more promising approach to the decompression problem has been proposed by Weathersby et al. (1984) using statistical methods to analyze real dive data and develop probabilistic models that can be used to develop decompression tables based on the risk of DCI.

Decompression tables based on deterministic methods are governed by a fixed set of rules that define the boundary between safe and unsafe dives. The NO-DECOMPRESSION LIMIT is a good example (Fig. 1). It is generally assumed that dive bottom times less than and up to the no-decompression boundary are safe. On the other hand, if this boundary is violated, it is assumed that DCI would result. However, we know that decompression and DCI are not this clear-cut, and some divers can develop DCI on the "safe" side of the boundary, while others on the "unsafe" side have no apparent problems. (A complicating factor is that different

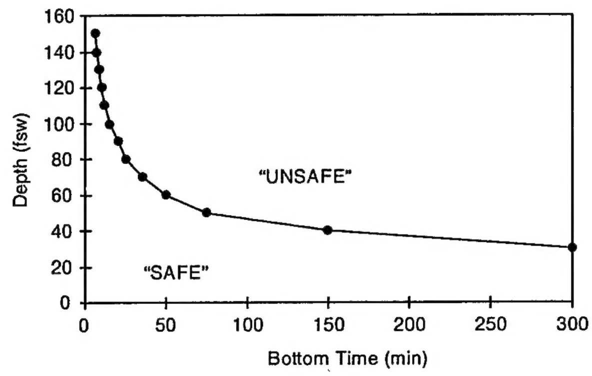


Fig. 1. No-decompression limit boundary

decompression tables may give entirely different no-decompression limits.) Individuals are different and may respond differently to a given stress. For example, one individual may incur DCI while many others on the same profile may have no problems. In addition, a given individual may respond differently on different days to the same profile.

Therefore, we have to consider DCI as a PROBABILISTIC EVENT (Fig. 2). It is no longer a

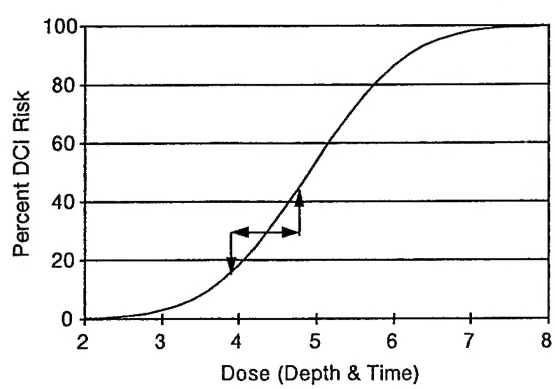


Fig. 2. Example of risk as a function of a depth/time dose

*Presented at tek.93, The Emerging Dive Technologies Conference, Orlando, FL, 18-19 Jan. 1993 and originally intended for publication in Hamilton, R.W. and M. Menduno (Eds.), *aquaCorps' tek.93* that was never published. This version has been updated with more recent references.

case of being just safe or unsafe. Increasing the time-depth dose increases the risk of DCI; decreasing it, decreases the risk. Thus, in the example given above, a dive table which has conservative no-decompression limits will have a lower risk of DCI than a table which has more liberal no-decompression limits. This concept leads to the statistical approach for developing probabilistic models of decompression to estimate or predict the risk of DCI.

DETERMINISTIC APPROACH

The deterministic approach (Fig. 3) requires a model for gas exchange that takes into account the pressure, time and gases used to calculate the gas loading or time-depth dose for an individual exposed to that pressure (Vann and Thalmann, 1993). There

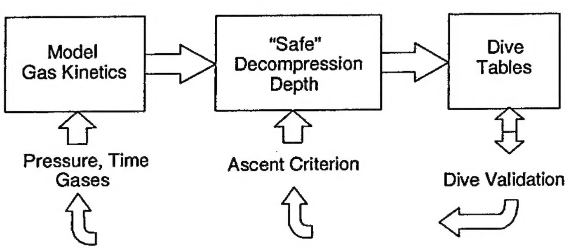
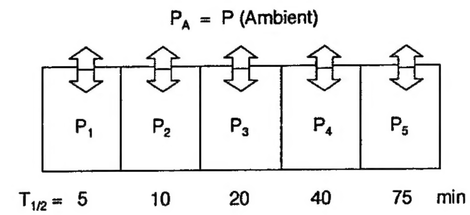


Fig. 3. Elements of a deterministic decompression model

must also be some form of an ascent criterion to enable the individual to return safely back to the surface. This ascent criterion defines the "safe/unsafe" boundary and is used to calculate the allowable or "safe" decompression depth at any given time. This ascent criterion can then be used to generate a decompression profile back to the surface or a set of dive tables. These must be tested to ensure their safety. In the event that the predicted decompression is inadequate, then it will be necessary to modify the model parameters and/or the ascent criterion until adequate decompression can be obtained.

The Haldane model is the classic example of a deterministic model (Fig. 4). Haldane assumed that the body could be represented by a set of parallel tissue compartments with different half-times representing fast to slow tissues. The half-times selected were from 5 to 75 min. The uptake and elimination of the inert gas were assumed to be exponential and were controlled by the half-times. Haldane's ascent criterion was simple. He assumed that the body could tolerate a certain degree of supersaturation, and that this supersaturation, the ratio between the allowable tissue pressure and the safe decompression depth, was a factor of 2.



$$\frac{dP_n}{dt} = k(P_A - P_n)$$

Ascent Criterion
Supersaturation Ratio

$$P_n = P_i - (P_i - P_A)\left[1 - e^{-0.693\frac{t}{T_{1/2}}}\right] \qquad \frac{P_n}{P_A} = 2$$

Fig. 4. Parallel tissue compartments decompression model (Haldane Model)

The US Navy found that the Haldane tables were not safe for deep or long dives (Workman and Bornmann, 1975; Hempleman, 1993). In the 1930's to 1950's, they showed that the faster tissues could tolerate a much higher supersaturation ratio than the slow tissues; for example, a value of 5.5 was used initially for the 5 minute compartment (Table 1). Continuing research also showed that a 120 minute half-time compartment was required for prolonged exposures at deeper depths and that the ratios were depth dependent, being lower at deep decompression stops. This was formulated into the M-value system of calculating decompression tables by Workman in 1965 (Hempleman, 1993) and further extended by Schreiner (Schreiner and Kelley, 1971) to include multiple inert gases that could be breathed simultaneously or sequentially.

Tissue Half-Times (min)	Haldane 1906	Hawkins, Shilling, Hansen 1935	Van der Aue 1951	Dwyer 1956	Workman M-Value 1965	
					M_0	ΔM
5	2.0	5.5	3.8		104	1.80
10	2.0	4.5	3.4		88	1.60
20	2.0	3.2	2.8	depth-	72	1.50
40	2.0	2.4	2.3	dependent	56	1.40
75	2.0	1.8 - 2.0	2.1		54	1.30
120			2.0		52	1.20
160					51	1.15
240					50	1.10

Table 1. Supersaturation ratios used by the US Navy

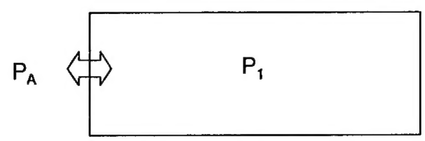
Implementation	No. of Compartments	Half-time Range	Application
US Navy	6	5-120	Standard Air Tables
Tonawanda II (Hamilton)	11 Nitrogen 11 Helium	5-670 5-240	Trimix Tables
Buhlmann	16	2.65-635	Swiss Air Tables
Rogers	14	5-480	DSAT (PADI) Recreational Dive Planner
Buhlmann-Hahn*	6	4-397	MICROBRAIN dive computer
Buhlmann (modified)*	6	4-320	ALADIN, US DIVERS dive computers
Powell*	12	5-480	OCEANIC dive computer
Nikkola*	9	2.5-480	SUUNTO dive computer
Huggins/Spencer*	12	5-480	ORCA dive computer
Lewis Multi-level*	6	5-120	OCEANIC dive computer
Lewis Modified, Spencer, Powell-Rogers	12	5-480	DACOR dive computer

*Source: Walsh M. "DIVE COMPUTERS, a Comparison by DACOR", Jan. 1990

Table 2. Examples of Haldane/Workman/Schreiner decompression models used in dive tables and dive computers.

The Haldane/Workman/Schreiner model, and its many derivatives, form the basis of most of the decompression tables and dive computers that exist today. Table 2 presents some examples, mostly for air diving, showing the number of compartments and range of half-times used. For example, the US Navy uses 6 compartments with a maximum half-time of 120 minutes. Tonawanda II represents a Schreiner version that is used for developing deep trimix tables, with 11 compartments each for nitrogen and helium. The maximum half-time for air is 670 minutes and for helium, 240 minutes. Buhlmann's air diving model uses 16 compartments (Buhlmann, 1984). The rest show other versions, modifications, and even combinations which are used mostly in dive computers (Walsh, 1990). All of these differ in the ascent criteria.

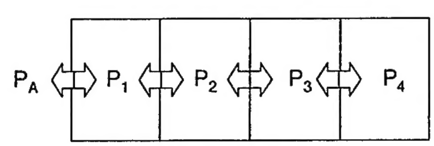
Although the Haldanian model is the most widely used model for calculating decompression tables, there are other models that have been proposed. These non-Haldanian models tend to be more complex mathematically. Of the several that have been developed, only two have been used to develop operational diving tables. The first is the single slab, bulk diffusion model (Fig. 5) that uses an approximation of the diffusion equation to calculate the uptake and elimination of gas (Hills, 1977; Hempleman, 1993). This model has been used to develop the Royal Navy air decompression tables, the British Sub Aqua Club tables, and Underwater Engineering Group commercial diving tables in the UK.



$$P_1 = P_A - \frac{8}{\pi^2}(P_A - P_0)\left[e^{-kt} + \frac{e^{-9kt}}{9} + \frac{e^{-25kt}}{25}\right]$$

Fig. 5. Single slab bulk diffusion model (British)

The second is the Kidd-Stubbs model (Kidd and Stubbs, 1969) which was modified and used to develop the DCIEM air and helium decompression tables (Nishi, 1992). It uses a series arrangement of four compartments (Fig. 6). The four differential equations that define the uptake and elimination of gas into the model are nonlinear and need to be solved by numerical techniques on a digital computer. Both the single slab and the series model have ascent criteria that are depth dependent.



$$\frac{dP_n}{dt} = A[(B + P_{n-1} + P_n)(P_{n-1} - P_n) - (B + P_n + P_{n+1})(P_n - P_{n+1})]$$

where $P_0 = P_A$ and $P_5 = 0$

Fig. 6. Serial compartments decompression model - (Kidd-Stubbs Model (Canadian/DCIEM))

The models used to calculate decompression tables are empirical and non-physiological models, and should properly be called decompression calculation methods, or decompression algorithms, rather than decompression models (Hills, 1997). The tissue compartments do not represent real tissues. There is no prerequisite for successful decompression table calculations to have a precise knowledge of the physiology or causes of decompression illness (Hempleman, 1969). In these deterministic decompression calculation methods, the equations and constants of the model have been selected to fit the data. If the equations or constants prove to be inadequate, then other equations or constants are introduced until a good fit is achieved.

With a Haldane/Workman/Schreiner model, there is an abundance of parameters (3 times the number of compartments) that can be altered independently to try to extend the operational envelope of the tables or to correct local problems. If a Workman/Schreiner formulation is used to expand the model to a matrix of M-values, then up to several hundred parameters can be adjusted to take care of difficult profiles. Although such models appear to have great flexibility, they are mathematically cumbersome and provide little insight of DCI or guidance for the development of a more realistic decompression model. Non-Haldanian models are generally better in this respect, having fewer parameters or degrees of freedom.

Deterministic models are generally restricted to a limited range of depths and bottom times and the development of a universal model which will predict decompression from no-decompression to deep long dives or even saturation dives appears too difficult or impossible to attain. In addition, with any deterministic model, it is impossible to calculate the risk if the ascent criterion is inadvertently violated, or to determine what corrective action should be taken.

Because DCI is considered a binary event, *i.e.*, either DCI occurs or does not occur, testing or validating profiles is difficult. The validation process for decompression tables requires testing profiles in several different stages, through chamber testing, operational evaluation of provisional tables, and field use (Hamilton and Schreiner, 1989). At each stage, there is a detailed analysis and review, and it may be necessary to start over after modifying or changing the model. The question becomes, how many dives must be done to declare a profile to be safe and advance to the next stage? This becomes more of a practical consideration rather than a statistical one, and often 20 dives without a DCI incident is generally considered to be acceptable.

If we do this, statistical theory tells us that the true incidence of DCI can be anywhere from 0% to 16.8% at the 95% confidence level. This is shown in Table 3 (Weathersby, 1990a). If we wanted to be 95% confident that our true incidence would be less than 1%, we would have to do 400 tests on that profile alone with no cases of DCI.

DCI Cases	Trials	% DCI	95% Confidence Limits on % DCI
0	5	0.0	0.0 - 52.2
0	10	0.0	0.0 - 30.9
0	20	0.0	0.0 - 16.8
0	50	0.0	0.0 - 7.1
0	180	0.0	0.0 - 2.0
0	400	0.0	0.0 - 0.9

Table 3. Uncertainty in single repeated trials with no observed DCI.

What are the implications of such a requirement? Suppose we want to test a dive profile that lasts three hours (bottom time and decompression time) at a hyperbaric chamber facility. Let us also assume that two dives a day can be conducted (in a five day work-week), with five subjects in each dive. Completing 400 man-dives would require 80 dives or 40 dive days (8 weeks). However, to avoid any acclimatization effect which may cause a dive subject to become more resistant to DCI, dive subjects must avoid diving every day. For air dives, a minimum of 36 hours is generally accepted as being necessary between dives for any given subject. For helium/trimix dives, a minimum of 72 hours should be maintained before the start of consecutive dives for any given dive subject. Thus, for helium dives with two dives a day, six teams of 5 dive subjects (at least 30 dive subjects) must be available for 8 weeks. If the dive profile is longer than three hours, it is most likely that only one dive a day could be done, thus requiring 16 weeks of diving (however, only 15 dive subjects would be necessary). Note that this example applies to only one profile.

This also assumes that no cases of DCI are encountered during these 400 dives. If DCI were to occur, then considerably more dives would have to be done to assure the 1% incidence at the 95% confidence level. Treatment for DCI (usually a

minimum of 6 hours is required) may delay the dive series, since the same chamber might be used for both experimental diving and treatment. If DCI is diagnosed soon after the dive is completed, the treatment would extend into the evening hours. If symptoms are delayed, treatment could well take place throughout the night. This raises the problem of having sufficient personnel to operate the chamber facilities for the treatment dive (*i.e.*, a replacement crew would have to be available, and overtime would have to be paid) and operate the chamber during the day for experimental diving. Chamber crews would soon suffer from "burn-out" under these circumstances. In addition, the dive subjects incurring DCI would be prohibited from further diving for several weeks, thus requiring replacements.

Obviously, it would be impossible to spend that much effort on only one profile. We don't have the time, the personnel, or the money to do this for every profile that we want to test and it is understandable that compromises have to be made, even to the extent of only doing 20 dives on one profile for acceptability. Fortunately, we do have some other cues to help us make our decisions, including past experience and a knowledge of the safety of other existing tables or related profiles. We also have Doppler ultrasonic monitoring of bubbles to give us further information on the decompression stress of the dives (Nishi, 1993a, b).

STATISTICAL APPROACH

The statistical approach to decompression modelling was developed at the US Naval Medical Research Institute (Weathersby *et al.* 1984, Weathersby *et al.* 1985a) and it has had a very large impact on how we now look at and treat decompression. In this approach, DCI is considered as a probabilistic event and we define a risk function based on the time-depth dose to estimate the risk or probability of DCI (Fig. 7). We can also use the risk function to compute an ascent profile such that the risk of DCI does not exceed a pre-selected acceptable level of risk, unlike the deterministic approach that calculates a "safe" ascent profile. To determine the risk function, we need a large data set of real dive data containing a reasonable number of cases of DCI as well as many uneventful dives, and we must fit the risk function to the observed data.

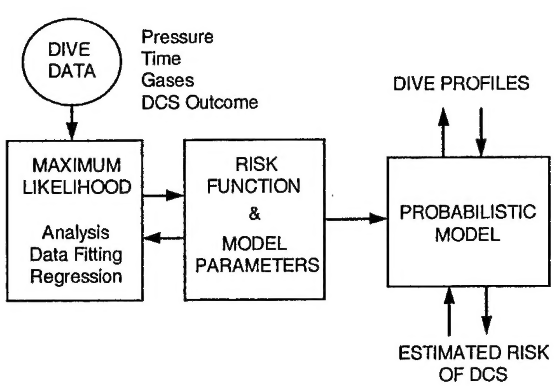


Fig. 7. Statistical model of decompression

The risk function contains both the gas kinetics and the ascent criteria. These are similar to those used in the deterministic approach. We can assume, for example, gas kinetics based on a two compartment model, consisting of a fast and slow tissue (Fig. 8). The ascent criterion could be based on the supersaturation as in the deterministic approach, or we could also use bubble growth as a criterion.

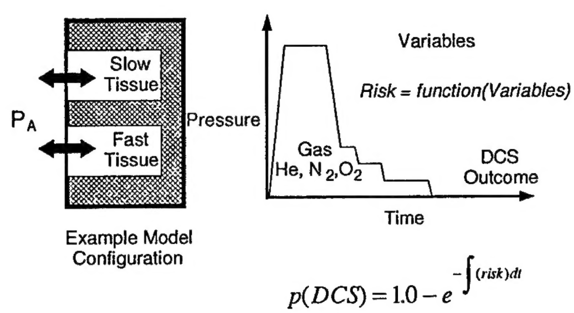


Fig. 8. Elements of the risk function for probabilistic model of decompression

Instead of selecting the parameters of our risk model beforehand as in the deterministic approach and using trial and error until the best fit to the data is achieved, we only need a rough estimate of the parameters as an initial starting point and then we let the parameter estimation program calculate the half-times and the other parameters that will give the best fit to the data. These parameters of the risk model are calculated iteratively by comparing the predictions of DCI with the observed data until we obtain the best fit. The method used is called the principle of maximum likelihood (Edwards, 1972).

We can extend this to any number of compartments and also determine what the optimum number of compartments and/or parameters should be using statistical tests. We are not necessarily restricted to a parallel configuration of compartments or exponential uptake or elimination of inert gases.

The best model that the US Navy has found for air diving is one using exponential uptake and linear elimination (Parker *et al.*, 1992a). We could also take an existing model, such as the Kidd-Stubbs model or a Haldane model (Vann, 1987; Parsons et al., 1989), to determine what the optimum parameters should be to fit existing data.

Normally, the predictions of DCI from our risk function are fitted against observed DCI values. If we use the bubble growth approach for the ascent criterion, we could also try fitting an estimated bubble size against Doppler bubble scores observed after dives (Gault *et al.*, 1995). Doppler-detected bubbles can give an indication of the decompression stress of dives. No detectable bubbles or few bubbles are indicative of low decompression stress, whereas large quantities of bubbles are always associated with high decompression stress, and a higher risk of DCI. Although high bubble levels do not necessarily result in DCI, experience has shown that DCI is almost always associated with high bubble levels (Nishi, 1993b). Thus, we could use the probabilistic method to develop a model for decompression stress.

The dive data set used to calibrate the statistical model is critical. The data must define the dive profile accurately, and must provide an accurate account of the outcome, whether or not DCI occurred and when, if it did occur. We need a very large data base of dives with and without DCI. In fact, we need many cases of DCI in our data set because the parameter estimation procedure must be able to distinguish between "safe" and "unsafe" dives (Albin, 1992). Not having enough DCI cases in a very large data set would lead to poor parameter estimates.

We also have to be very selective in the data that we can accept as primary. Not all data can be used. We need a detailed account of the dive profile from the start of the dive to the end of the decompression. We cannot just use the nominal depth and bottom time reported by a diver and assume decompression occurred according to the stop times taken from the decompression table that was used. We need the true profile including any delays and depth variations (Fig. 9). The time resolution must be within 0.3 minutes during depth changes and gas mixture changes, and depths must be precise to within 1.5 feet of seawater (Weathersby and Survanshi, 1991). Gas composition must be known to within 1%. Operational dive logs generally do not give sufficient detail since they only state "left surface", "reached bottom", "left bottom", and so on. Chamber logs, where there are accurate records of time and pressure, not just the nominal depth and bottom-time, and which have been medically monitored as to DCI outcome, are ideal. We must also know the time when the first definite symptom of DCI occurred (Weathersby *et al.*, 1992a).

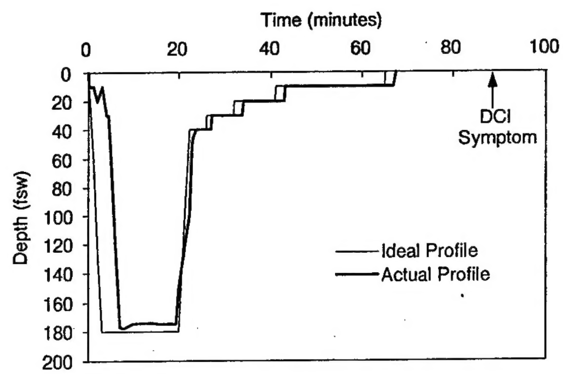


Fig. 9. Data requirements for probabilistic modelling - actual dive profile vs. ideal table profile

Historical chamber logs from dives which were done in the 1940's to the 1960's to develop decompression tables and which contain many cases of DCI, may seem ideal but are generally not suitable because the criteria for DCI were different at the time. For example, during the development of the US Navy tables, symptoms had to be far more severe than today's standards before they were classed as decompression illness and treated (Weathersby *et al.*, 1986a). Thus, we cannot use these data to develop diving procedures that are safe according to present day criteria for DCI.

Open water dives done with dive profile data loggers could qualify if the times and depths have been recorded several times a minute, or at the worst, at 20 second intervals. However, we may not be able to use these data unless the DCI outcome has been reported accurately and truthfully, preferably by a qualified diving medical specialist. It has been said that the first symptom of DCI is denial. In some cases, symptoms of DCI are ignored or not reported, wilfully or through a lack of recognition of symptoms of DCI. It is particularly important that marginal symptoms of DCI, which are often ignored since they may not require treatment, be reported because this information is valuable in defining the "gray" zone between no DCI and DCI. This is one area where technical divers could contribute because some are already diving with data loggers and are performing deep and long dives which push existing tables to the limit or are diving with new tables with mixtures other than air. If we could be confident of the quality of the depth/time and gas composition/gas switching data

and with the DCI outcome of these records, we could use these data. However, bad data are worse than no data. Incorrect information could lead to highly inappropriate and incorrect parameter estimates that may grossly underestimate the risk of DCI, leading to the development of hazardous decompression tables or procedures.

The power of the statistical approach is that we can now overcome the problem faced with the deterministic approach of having to do so many tests on a single profile. We can combine data from a wide variety of depth-time exposures to use in our data set even though each individual profile in the data set may constitute only a very small number of human tests (Weathersby, 1989). For example, the air data set used by the US Navy and which forms the basis of their new air and nitrogen-oxygen probabilistic decompression tables (Parker *et al.*, 1992b; Survanshi *et al.*, 1992a; Kelleher et al., 1992) consists of more than 3300 man dives from DCIEM, the US Navy and the Royal Navy, done from 1977 to 1990 (Weathersby *et al.*, 1992b). The data range from submarine escape profiles from depths as great as 600 feet with a total exposure time of less than 2 minutes, to saturation dives taking over a week long at pressure.

As more dive data become available, they can be added to the combined data set to improve the model parameter estimates and increase our confidence in the model. If we add helium or trimix dive data, both non-saturation and saturation, to an air diving data set, we could develop a probabilistic model which would also predict the risk for helium/trimix diving in addition to air diving. Thus the probabilistic model has the potential of being the universal model which can handle any gas and any depth-time exposure. However, we need high quality dive data if we wish to attain this goal.

A problem with the probabilistic method is that the parameter estimation program is very computation intensive, particularly if the calibration dive data set is large, and could require many hours or even days on a fast computer. The more complex the model, the more parameters that must be estimated. However, it may not be necessary to have complex models and the parameter estimation program may show that there is no advantage to using a complex model over a relatively simple one.

Once a probabilistic model is derived, we can look at dive profiles or dive procedures and estimate the risk of DCI or, conversely, we can calculate dive profiles or develop new decompression tables with pre-selected degrees of risk.

Fig. 10 gives an example of calculating the risk of DCI for the individual profiles in a set of tables. The figure shows the results for the new DCIEM helium-oxygen decompression table with in-water oxygen decompression (DCIEM, 1992). The risk model used took both helium and nitrogen into account (Tikuisis, 1991a) and was based on a preliminary data set (not well-calibrated) of approximately 3500 man-dives, of which approximately 30% were air dives. The estimated risk of DCI for the profiles of each bottom time/depth combination in the tables are divided into several different ranges of risk. The risk increases as we increase the bottom time at each depth. The high risks at the outer limits of the tables are a result of insufficient data for long and deep exposures in the preliminary helium data set. As a result, this model over-predicts the risk at the extreme limits of the table. The actual observed incidence of DCI in this range was around 3 to 5 percent during the validation trials for the helium decompression tables.

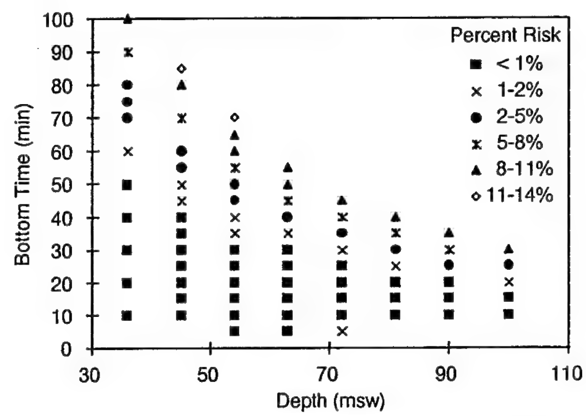


Fig. 10. Example of risk prediction - predicted risk of DCI for DCIEM 84/16 Surface-Supplied HeO_2 Table

The same type of analysis can be used to compare different decompression tables and to estimate the relative risks of DCI (Weathersby *et al.*, 1986b). We can also look at profiles which give a high risk of DCI and determine how to change these profiles to decrease the risk. Dive procedures can also be analyzed such as repetitive diving (Tikuisis, 1992; Gerth *et al.*, 1992). Another possibility is to look at the relative risks of different dive conditions, for example, between wet and dry chamber divers (Weathersby *et al.*, 1990b), and introduce into the risk function a factor to take the difference into account for future predictive purposes. This method may also be applied to estimate the risk of DCI for divers with predisposing conditions (Tikuisis *et al.*, 1991b).

Table 4 shows an example of equal risk decompression tables developed by the probabilistic method (Weathersby *et al.*, 1985b). These are no-decompression limits for air dives with a 1% and 5% estimated risk of DCI. Selecting a 1% risk severely restricts the allowable time at depth; for example, at 100 feet, only 8 minutes is allowed. This is considerably shorter than, for example, the 15 minutes allowed by the DCIEM air table, or the 25 minutes allowed by the present US Navy tables. However, if the higher risk of 5% is acceptable, a much longer period, 50 minutes in this case, can be spent at 100 fsw. The choice of the acceptable risk level will generally be an operational decision. (Note that these tables were developed from an early US Navy study and are not necessarily the same as the recently completed probabilistic air tables. Table 4 illustrates what can be done with probabilistic models.)

Depth (fsw)	No-Decompression Limit (min)	
	1%	5%
30	170	240
40	100	170
50	70	120
60	40	80
70	25	80
80	15	60
90	10	50
100	8	50
110	7	40
120	5	40
130	5	30

Table 4. Example of statistically-based decompression tables - equal risk no-decompression limits (source - Naval Medical Research Institute NMRI 85-17, Mar. 1985)

In addition to tables of equal risk, tables can also be developed with variable risk in different depth/bottom time ranges, depending on operational requirements. Unlike the deterministic model which gives only one path back to the surface, the probabilistic model can give an infinite number of paths back to the surface, depending on the risk that the user is willing to tolerate or accept. One obvious choice is to generate tables which minimize the decompression times for a given risk. Regardless, any decompression table or profiles developed from probabilistic models will still require validation testing under controlled conditions. Fortunately, strategies can be devised for minimizing the number of trials and cases of DCI while still retaining the statistical power of the method, for example, by using a sequential trials design (Homer and Weathersby, 1985; Survanshi *et al.*, 1992b; Lehner and Palta, 1989).

Probably the greatest advantage of the probabilistic model is that it can be designed into a real-time dive computer to give considerable flexibility and decompression options (Survanshi *et al.*, 1996). For example, the computer can be constantly calculating the instantaneous risk as the dive progresses and determining the optimum decompression profile to minimize the total decompression time for a given risk level (Survanshi *et al.*, 1992a). Such a real-time algorithm requires considerable processing power and it is unknown at the present time when it would be possible to implement the program in a miniature diver carried dive computer.

Although probabilistic models have been successful in predicting observed DCI in a wide range of air and nitrogen-oxygen dive data, they have tended to underpredict the risk of DCI for dives with prolonged breathing of 100% oxygen. Studies have shown that it is highly possible that oxygen may have to be treated as a contributor to DCI risk at high partial pressures (Parker *et. al.*, 1996).

Another application of the probabilistic approach has been the development of a model for predicting maximum bubble size calibrated against Doppler-detected bubbles in divers (Gault *et al.*, 1995). Remarkably, the predictions agree closely with those from an independently-derived bubble model calibrated against the incidence of DCI that has been used to generate a Bubble Grade Index (BGI) (Gernhardt, 1991). Fig. 11 shows a comparison of the maximum bubble size predicted from the DCIEM model and the BGI for no-stop decompression dives.

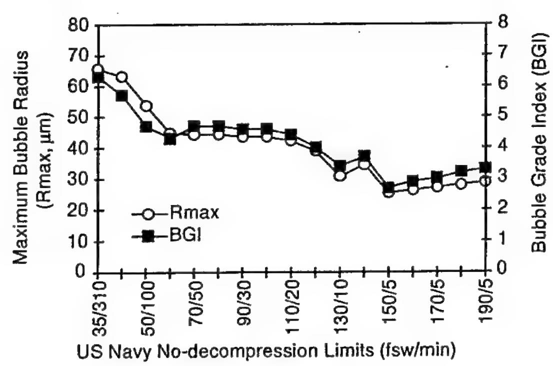


Fig. 11. Comparison of predicted maximum bubble size based on Doppler-detected bubbles with the Gernhardt Bubble Grade Index based on DCI data, for US Navy no-decompression dive limits.

The close agreement strongly supports an inherent connection between bubble size and the incidence of DCI, and by extension, the application of bubble models for safe decompression. Preliminary investigations indicate that decompression is incident-free if the maximum bubble size or BGI is below a specific threshold. This potentially provides a very convenient method for developing safe surface decompression procedures.

In summary, the probabilistic approach for decompression is a very powerful technique that opens up the potential for an entirely new concept in table design, analysis, and dive testing. It is highly desirable because of its objectivity and its potential for implementing gas kinetics and bubble physics in the design of the risk function for DCI. By being able to investigate different risk criteria, for example, gas supersaturation *vs.* bubble growth, bubble size *vs.* gas volume, *etc.*, and matching the results to actual dive data, we should be able to gain a better insight into the physics and physiology of decompression. At the present time, we can still be considered to be in the developmental stages, trying to find the best risk model, establishing well-calibrated dive data for helium/trimix dives, and exploring the potential uses of the probabilistic decompression models. There are still many problems to be overcome before we can achieve the universal decompression model.

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Since the development of the first decompression tables in 1906 by J.S. Haldane, considerable research and effort have been expended in the development of safer and more rapid decompression procedures and tables. The deterministic approach is governed by a fixed set of rules that defines the boundary between safe and unsafe dives and includes a model for gas exchange and an ascent criterion, such as gas supersaturation, to calculate the "safe" decompression depth. These decompression models are essentially empirical and not physiological models and provide "safe" decompression only over a limited range of depth and bottom times. The statistical approach considers DCI to be a probabilistic event and uses a risk function consisting of a gas exchange component and an ascent criterion to estimate or predict the risk of DCI. The ascent criterion can be based on supersaturation or bubble growth. To determine the risk function, a large data set of precise dive data, including time, depth, gas composition, and DCI outcome, must be available to match the predicted risk with the observed data. Probabilistic models of decompression can be used to analyze dive tables and procedures, compare different tables, and develop decompression tables with a given risk level. The probabilistic approach for decompression is a very powerful technique that should lead to a better insight into the physics and physiology of decompression because of its objectivity and potential for implementing gas kinetics and bubble physics in the design of the risk functions for DCI. This should in turn lead to better table design, analysis and dive testing.

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